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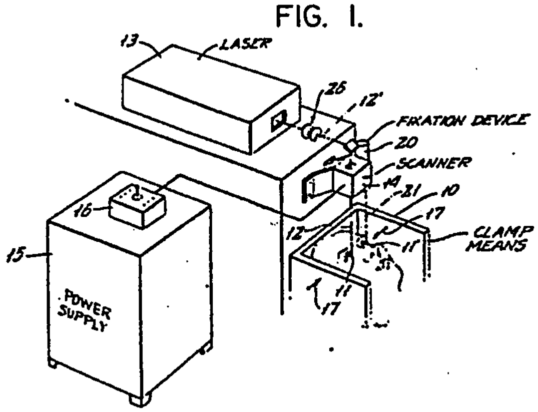
(54) **Method and apparatus for ophthalmological surgery.**

(57) The invention contemplates use of a scanning laser characterized by ultraviolet radiation to achieve controlled ablative photodecomposition of one or more selected regions of a cornea. Irradiated flux density and exposure time are so controlled as to achieve desired depth of the ablation, which is a local sculpturing step, and the scanning action is coordinated to achieve desired ultimate surface change in the cornea. The scanning may be so controlled as to change the front surface of the cornea from a greater to a lesser spherical curvature, or from a lesser to a greater spherical curvature, thus effecting reduction in a myopic or in a hyperopic condition, without resort to a contact or other corrective auxiliary lens technique, in that the cornea becomes the corrective lens. The scanning may also be so controlled as to reduce astigmatism and to perform the precise incisions of a radial keratotomy. Still further, the scanning may be so controlled as to excise corneal tissue uniformly over a precisely controlled area of the cornea for precision accommodation of a corneal transplant.

FIG. I.



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METHOD AND APPARATUS FOR OPHTHALMOLOGICAL SURGERY

BACKGROUND OF THE INVENTION

The invention relates to that aspect of ophthalmological surgery which is concerned with operations upon the external surface of the cornea.

Operations of the character indicated include corneal transplants and keratotomies; such operations have traditionally required skilled manipulation of a cutting instrument. But, however keen the cutting edge, the mere entry of the edge into the surface of the cornea necessarily means a wedge-like lateral pressure against body cells displaced by the entry, on both sides of the entry. Such lateral pressure is damaging to several layers of cells on both sides of the entry, to the extent impairing the ability of the wound to heal, and resulting in the formation of scar tissue.

The CO_2 laser has been employed in an effort to minimize such surgical damage to cells on severed sides of a given cut, as in the case of operations to remove a local skin defect. The beam of such a laser is characterized by a particular infrared wavelength (10.6 microns), and controlled local ablation or incision of the cornea is achieved, without developing any lateral pressure upon cells adajcent to the margins of ablation. However, the operation is not performed without side effects, in that the ablation or incision is thermally achieved, through photocoagulation and/or photovaporization; cells adjacent the ablated or incised margin are charred. And even with lasers emitting in the visible spectrum, the effect is still largely thermal in nature. For example, for visible laser irradiation of the skin at about 532.0 nanometers (0.532 micron), namely, in the pea-green portion of the visible spectrum, histological examination reveals evidence of cellular dehydration (i.e., cellular retraction with formation of tissue clefts, pyknotic nuclei) at energy densities where ablation can be accomplished; thus, at an energy level needed for ablation or incision with such radiation, charring (cellular damage) is observed at the site of the incision and is an indication of substrate heating.

On the other hand, radiation at ultraviolet wavelengths is characterized by high photon energy, and this energy is greatly effective on impact with tissue, in that molecules of tissue are decomposed on photon impact, resulting in tissue ablation by photodecomposition.

Molecules at the irradiated surface are broken into smaller volatile fragments without heating the remaining substrate; the mechanism of the ablation is photochemical, i.e., the direct breaking of intra-molecular bonds. Photothermal and/or photocoagulation effects are neither characteristic nor observable in ablations at ultraviolet wavelengths, and cell damage adjacent the photodecomposed ablation is insignificant.

BRIEF STATEMENT OF THE INVENTION

It is an object of the invention to provide an improved apparatus and technique for surgically operating upon the outer surface of the cornea.

Another object of the invention is to provide apparatus and technique for surgically modifying optical properties of the eye through surgical procedure on the outer surface of the cornea.

It is a specific object to provide surgical techniques and apparatus for reducing a myopic, for reducing a hyperopic, and/or for reducing an astigmatic condition of an eye.

Another specific object is to provide an improved surgical technique in performing corneal-transplant operations.

A still further specific object is to provide automatic means for safely applying ultraviolet irradiation in surgical procedures on the cornea.

The invention achieves these objects with apparatus which effectively fixes the position of an eye with respect to a scanning laser characterized

by ultraviolet radiation, at an energy level capable of achieving controlled ablative photodecomposition of the cornea, namely, of the epithelium, Bowman's membrane, and stroma levels of the cornea. Irradiated flux density and exposure time are so controlled as to achieve desired depth of the ablation, which is a local sculpturing step, and the scanning action is coordinated to achieve desired ultimate surface change in the cornea. The scanning may be so controlled as to change the front surface of the cornea from a greater to a lesser spherical curvature, or from a lesser to a greater spherical curvature, thus effecting reduction in a myopic or in a hyperopic condition, without resort to a contact or other corrective auxiliary lens technique, in that the cornea becomes the corrective lens. The scanning may also be so controlled as to reduce astigmatism, and to perform the precise incisions of a radial keratotomy. Still further, the scanning may be so controlled as to excise corneal tissue uniformly over a precisely controlled area of the cornea for precision accommodation of a corneal transplant.

DETAILED DESCRIPTION

The invention will be illustratively described in detail, in conjunction with the accompanying drawings, in which:

Fig. 1 is a schematic diagram in perspective, to show the general arrangement of operative components of the invention;

Fig. 2 is a simplified view in longitudinal section, showing an eye-retaining fixture used with the apparatus of Fig. 1;

Figs. 3 and 4 are simplified diagrams to illustrate different scan patterns performed with apparatus as in Fig. 1;

Figs. 5 and 6 are simplified sectional views to illustrate different sculptured surface curvatures achieved with either of the scan patterns of Figs. 3 and 4;

Figs. 7 and 8 are views in section, and Fig. 9 is a view in front elevation, to illustrate use of the invention in a corneal transplant operation;

Fig. 10 is a view in front elevation to illustrate use of the invention in a radial keratotomy operation;

Figs. 11 and 12 are, respectively, a view in front elevation and an enlarged half-section-profile diagram to illustrate a Fresnel-cut use of the invention;

Fig. 13 is a schematic diagram to illustrate modified apparatus to generate the scan pattern of Fig. 3; and

Fig. 14 is a similar schematic diagram to illustrate modified apparatus to generate the scan patterns of Fig. 4.

In Fig. 1, clamp means 10 is shown for fixed retention of the head of a patient (reclined, face up) such that the eye 11 to be operated upon is fixedly aligned with a downwardly folded portion 12 of the central axis 12' of beam output from a stationary laser device 13, and scanner means 14 is provided for programmed deflection of laser-beam output, with respect to the central axis 12. The laser device 13 is served by a suitable power supply 15, and the scanner means 14

includes selectively operable control means, symbolized at 16, for determining scan pattern, effective limits of scan action, and, if desired, the time-varying profile of one or more dimensional components of scan action.

Preferably, the clamp means 10 includes means, symbolized at 17, to stabilize the patient's head via opposed engagements at the region of his temples, and an eye-retaining fixture (18, Fig. 3) peripherally engages eye 11 at the corneal-scleral area. Also preferably, an optical-fixation device 20 is adjustably fixed, as to the housing of scanner 14. Illustratively, device 20 includes a sighting reticle and lens, whereby the eye 11' not being operated upon can view the reticle as if at infinity; the sighting alignment 21 for device 20 is parallel to the axis 12, and it will be understood that adjustable means (not shown) may provide an adjustable offset, as needed for accommodation of the patient's interpupilary distance and to adapt to the particular mounted offset of device 20 from axis 12. For an operation on the other eye 11', the eye 11 will be available for similar fixation, in conjunction with another fixation device (not shown) and associated adjustably offsetting means; alternatively, the fixation device 20 may be adjustably mounted at correct offset on the opposite side of scanner 14. For purposes of operating on eye 11', clamp means 10 will have been indexed laterally with respect to laser 13 to the extent aligning axis 12 with the eye (11') then to be operated upon, thereby positioning eye 11 for use of the fixation device.

The eye-retaining fixture 18 of Fig. 2 is seen to comprise a hollow annulus, having a convergent axial-end wall 23 of air-permeable material contoured to engage and retain the eye via a scleral-corneal region. A side-port connection 24 to a vacuum pump enables retention of eye engagement to wall 23, and outward lug or flange means 25 enables rigid aligned and spaced connection of fixture 18 to laser 13 and its scanner 14 via means suggested by legend in Fig. 2, such means being omitted from Fig. 1 for reasons of more simplified showing.

The laser selected for use at 13 preferably emits in the ultraviolet, namely, at wavelengths of less than substantially 400 nanometers. Such emissions for gas lasers are characteristically at 351 nm for xenon-fluoride lasers, 337 nm for nitrogen lasers, 308 nm for xenon-chloride lasers, 248 nm for krypton-fluoride lasers, 193 nm for argon fluoride lasers, and 157 nm for fluorine lasers; and within this range, frequency-doubling techniques applied to other lasers, including crystal lasers, provide further alternative sources.

One of the existing commercial excimer-laser products of Lambda Physik GmbH, Gottingen, Germany, for example their Model EMG 103 operating with argon-fluoride, is satisfactory for use as laser 13; for this product, maximum energy per pulse is 200 millijoules, with a pulse-repetition rate of 200 per second, 3 X 10^5 shots being available from a single charge of the involved gas, before reducing to 50 percent of specified power at this repetition rate, it being noted that full rated power

is not necessarily required in use of the present invention. Pulse width is about 15 nanoseconds, and typical beam dimensions at 25 centimeters (10 inches) are 10 mm x 22 mm. To bring this down to an illustratively useful rounded-square spot size of 0.5 mm by 0.5 mm at the eye 11, corrective lens elements at 26, as of quartz, calcium fluoride, or magnesium fluoride, will be understood to include a cylindrical element and a spherical element whereby beam size is reduced while the rectangular section is compressed to substantially square section.

Figs. 3 and 4 illustrate alternative scan patterns for having the typical half-millimeter focused and repetitively pulsed spot of the laser beam course the surface of eye 11 in the performance of a surgical procedure. The circle 30 in Fig. 3 may illustratively be of 6-mm diameter at the cornea, and centered on the axis of eye 11. The scan action is rectilineal, involving plural horizontal line scans with progressive vertical displacement to cover the field, here shown limited to the circle 30. For this purpose, a suitable scanner, known as "Microscan 771", is commercially available from Laser Industries International, Hendon, England and therefore need not be here described in detail. It suffices to say that the control means 16 associated with such a scanner includes a microprocessor with memory for delineated boundary limits of scan, such as the limiting circle 30. The delineation can be to the surgeon's desired boundary contours, and the scan speed and direction may be programmed or manually controlled. What has been

said as to Fig. 3 also applies to Fig. 4, except that a spiral course of scan, i.e., rotary sweeps at progressively changing radius, is involved in each coverage of the delineated field 30'.

It is a feature of the invention that the programming of scan action be such that predetermined depth of ultraviolet laser incision be made to effectively recharacterize the external contour of the cornea within the entire predetermined field boundary (e.g., 30, 30'). This is done by progressive precise photodecomposition of the corneal tissue, as to a depth limit of 0.35 mm. In the illustrative argon-fluoride laser referenced above, a precise volume of tissue (e.g., 14 microns deep) may be excised for each laser pulse or shot, and the half-millimeter spot, repeated at 200/second, can cover the entire area within the delineated boundary 30, in about fifteen seconds.

For the situation depicted in Fig. 5, the dashed line 31 represents the ultimate curvature to which the external surface of a cornea 32 may be modified to achieve a change in optical properties of the involved eye, here illustratively a myopic eye, for which the reduced curvature 31 offers a diopter-reducing corrective effect, all without resort to the use of a spectacle lens or a contact lens to achieve the result. To achieve the curve 31, the minimum desired photodecomposition is at the outer boundary 30, and the maximum is at the center. This is achievable by programming the microprocessor to progressively reduce the radius of the boundary circle 30 (i.e., progressively reduce the area of scanned field),

for successive scans of the reducing field. If the curvature 31 requires a maximum depth of 0.35 mm of cornea removal at the center, this means that the central region of the cornea (i.e., the last and most reduced scanned field) will have been scanned twenty-five times, and that cornea removal outside this most reduced scanned field will have involved lesser numbers of scans, the progression having been predetermined to achieve the desired ultimate curvature 30 over the area 31.

What has been said as to the scan technique of Fig. 3 to achieve curvature 31 applies equally for use of the spiral scan of Fig. 4, the field 30' again being programmed for automatic reduction as necessary to provide maximum cornea removal at the center, and minimum at outer limits of the circular boundary.

What has been said as to programming to achieve lesser curvature in the outer surface of the cornea (Fig. 5), to reduce a myopic condition, applies also to Fig. 6 for reduction of a hyperopic condition. In Fig. 6, the difference lies in programming field scans so as to initiate and progressively enlarge a central area which defines the inner limit of field scanned. Thus, except for perhaps one field scan involving cornea removal over the entire area bounded by circle 30 (30'), all remaining field-scanned areas are annular, with progressively increasing inner radius of each successively scanned annular field. The last such "field" will necessarily be virtually a circular line at the diameter of circle 30 (30'), along which

circular line the depth of surgical excision will have been greatest, as indicated by dashed line 33 in the cornea 34 of Fig. 6.

Quite aside from the variable-depth character of the removal of corneal tissue (Figs. 5 and 6), the invention also lends itself to uniform-depth removals, over the entire area of a multiply-scanned constant field. In Figs. 7 and 9, the cornea of an eye 11 is subjected to a succession of scans of (i.e., within) a constant predetermined field area 35. In the illustrative laser case, with excision to a depth of 14 microns for each pulse, a uniform depth of 0.35 mm is achieved by 25 scans of the total area 34, to produce a carved base or floor curvature 36 for reception and location of a corneal transplant.

Further with respect to a corneal-transplant procedure, the described apparatus will be seen to be further useful, as in preparation of the corneal insert to be implanted at and within the recess 36. A donated eye may be reversibly held to a fixture as described at 18 in Fig. 2; by "reversible" it is meant that, depending upon the manner of mounting flange 25, either the epithelium or the endothelium of the donated eye may be mounted for upward exposure to the laser beam 12, it being understood that for the latter situation with the donated eye, iris and other regions not needed for corneal-scleral mounting and for corneal operation will have been initially removed. A preferred procedure is first to so expose to laser

scanning the concave inner side of the donated cornea; such scanning is to an extent (achieved by multiple scans of a full circular field exceeding the diameter of recess 36) sufficient to remove tissue at least to a uniform depth within the stroma, whereupon the mounting of fixture 18 (and its partially machined corneal workpiece) is reversed, to expose to laser scanning the convex outer side of the donated cornea. Scanning the outer side consists of two steps: first, multiple scans of the full circular field (exceeding the diameter of recess 36), thereby excising at least the epithelium and to a depth which preferably achieves a transplant thickness T_1 exceeding the depth T_2 of recess 36; second, scanner 14 is operated in a line-cutting mode wherein successive laser pulses sequentially advance along the circumference of a circle designed for precise acceptance in the circular recess 36, until full severance of the circular cut-out, which then becomes the prepared transplant. Upon implanting, donated stroma is placed in full endothelium-free contact with the patient's prepared stroma, and the implant may be sutured. Later, upon removal of sutures, the outer surface of the eye 11 and its transplant 27 will have the appearance shown in Fig. 8, wherein the transplant projects beyond adjacent areas of the patient's cornea, and this projecting surface of the transplant may be reduced by laser scanning to a finish contour 28 of preferably flush marginal conformance with non-sculptured adjacent tissue of the

patient's eye. It will be further understood that, subject to the surgeon's decision, such a finishing cut may be to a curvature which does or does not effect a predetermined change in optical performance of the eye.

Fig. 10 illustrates a modified use of the described apparatus, as for developing the plural angularly spaced radial cuts 37 involved in a radial keratotomy, all within a predefined circular limit 38. Depending upon the severity of the condition which calls for a kerototomy procedure, the depth of radial cuts 37 may exceed the 0.35 mm depth illustratively given for Figs. 5 to 8.

Certain myopic and hyperopic conditions may be so severe that to produce merely an excised single surface 31 or 33 could involve, in the surgeon's considered judgment, an excessive removal of tissue, at the involved region of necessarily deepest cut. For such a situation, the invention offers the option of programming successive scans in a manner to create a Fresnel-type stepped development of the desired ultimate curvature. Such a situation and procedure are illustrated in Figs. 11 and 12, wherein an ultimately reduced-curvature surface 31 of Fig. 5 (dashed line 41 in Fig. 12) is achieved in annular increments within the field area bounded at 30. In the outer one of these annuli (42), the curvature and depth of cut are precisely as would have applied to generate the continuous curve 41 (i.e., without Fresnel steps). But the intermediate

annular area 43 effectively achieves a continuation of curve 41 with much less volume of corneal excision. Finally, the inner circular area 44 effectively completes curve 41, with minimal removal of corneal tissue.

The removal of tissue at the center is denoted Δ_{44} for the Fresnel cut 44 of Figs. 11 and 12 and, comparatively, is but a small fraction of the maximum removal depth Δ_{41} which would be needed to achieve the same optical correction with the smoothly developed corrected single-curvature surface 41. It will be understood that for a Fresnel-type cut as illustrated in Fig. 12, the previously described illustrative half-millimeter spot size will be incapable of achieving the desired result, for the one-millimeter radial increments shown in Fig. 12. To produce the requisite resolution for characterizing increments of curvature 41 at 42, 43, 44, it is necessary to employ a smaller spot size. For the indicated Lambda Physik equipment, spot-size reduction is feasible via means 26 as far as to produce a 30-micron spot size, if necessary; with this capability, it is seen that the one-millimeter radius increments of annulus 42 and annulus 43 are each achievable with a resolution of about 35 radial steps per increment (42 or 43). It will thus be understood that numbers given above are for purposes of more simplified illustration of this and the other aspects of the present invention.

Figs. 13 and 14 serve to illustrate that scanner action may be achieved by means other than the reflective techniques of the Laser Industries device mentioned above. In Figs. 13 and 14, the deflection of beam 12 for

scanning purposes is via transverse magnetic fields, in the manner of a deflection yoke for a cathode-ray tube. In Fig. 13, the yoke 50 is annular and is mounted for rotation about beam 12, as by a manually adjusted edge drive 51, with suitable means 52 to indicate the currently operative extent of angular adjustment. Yoke 50 carries orthogonally related deflection-coil systems 53-54 which receive signals from suitably synchronized X-axis and Y-axis sources 55-56, for rectilineally scanned deflection of beam 12 at the eye 11; legends identify envelope-limiting means associated with the deflection-signal generators and coordination with enable/disable functions of the laser whereby the laser beam is only operatively scanned over the desired limited area of the cornea (e.g. area 30). It is a feature of the invention that by suitably programming the rate of scan of one of these scan axes, for example, the X or line-scan deflection axis, the rate can be relatively slow at outer limits and relatively fast in regions between outer limits of each scan (all as suggested by X-rate profile means 57), with the result that the greater density of pulsed-laser shots will impact the latter regions, while the Y-axis component of scan development remains steady; alternatively, the Y-axis component may be under a varying rate control (58) while the X-axis sweeps are linear. The result is to develop an astigmatic curvature of cylindrical nature, which may be oriented according to the preset angular direction set at 52. The prospect is thus to effect astigmatic correction in a given eye 11, without resort to an artifical element such as a lens.

The magnetic deflection system of Fig. 14 also employs a rotatable yoke 60, but the employment is to develop a polar-coordinate scan pattern, or to develop the spiral-type pattern referred to in connection with Fig. 4. More particularly, a single radial-deflection coil system 61 is served by a radius-scan sweep-signal generator 62, and rotary sweep is via a motor 63 having edge-drive connection to yoke 60. A polar raster generator 64 coordinates the speed of motor 63 with sweep cycles of generator 62. And the specific spiral scan of Fig. 4 is achieved by making the radial sweep cycle of generator 62 so slow with respect to rotation of yoke 60 that plural rotations are involved for each radial sweep. On the other hand, for slow rotation of yoke 60 and many radial sweeps for each such rotation, a polar scan is developed for the delineated field. If the signal output of generator 62 is sufficient to cause a full diameter of sweep for each sweep cycle, the central region of the field will receive the greatest density of shots and will therefore be subjected to maximum excision; the field will therefore be covered once for each half revolution of yoke 60. The result of such shot-density distribution is to approach the requirement for curvature reduction, as discussed in connection with Fig. 6, and it will be understood that rate-profiling control of the radius-scan signals at 62 offers further latitude in the development of ultimate curvature upon completion of scanning.

CLAIMS:

1. Sculpture apparatus for operation upon the external surface of the cornea of an eye of a patient, comprising laser means having a chassis and producing an output beam in the ultraviolet portion of the electromagnetic spectrum, scan-deflection means positioned for deflection of said beam, and body-engageable means for steadying one eye of the patient with respect to said chassis and with a corneal portion of said one eye within a field traversed by scan deflection of said beam.

2. Sculpture apparatus according to claim 1, and eye-fixation means fixed with respect to said chassis and aligned for observation through the other eye of the patient.

3. Sculpture apparatus according to claim 1, wherein said laser means is an excimer laser operative with a gas selected from the group comprising fluorine, argon fluoride, krypton fluoride, xenon chloride, and xenon fluoride.

4. Sculpture apparatus according to claim 1, wherein said laser means produces an output beam characterized by a wavelength not substantially exceeding 400 nm.

5. Sculpture apparatus according to claim 1, in which said scan-deflection means comprises mechanically displaceable optical components, and means for displacing the same to effect a predetermined deflection of said beam.

6. Sculpture apparatus according to claim 1, in which said scan-deflection means includes an electromagnetic deflection yoke, and deflection-signal generator means connected to excite said yoke for effecting a predetermined displacing of said beam.

7. Sculpture apparatus according to claim 6, in which said yoke is annular and is mounted for rotation about said beam, said yoke being connected for excitation to generate radial deflection of said beam.

8. Sculpture apparatus according to claim 6, in which said deflection yoke includes two defection systems which are individually operative to effect orthogonally related components of beam deflection.

9. Sculpture apparatus according to claim 8, in which said yoke is annular and is mounted for rotation about said beam, said yoke being connected for separate excitation of the respective deflection systems, and the excitation of at least one of said deflection systems being characterized by varying amplitude which is a non-linear function of time.

10. Sculpture apparatus according to claim 1, in which said laser means includes a means for reducing its beam size at the eye of the patient to a spot size in the range 30 microns to 0.5mm.

11. Sculpture apparatus according to claim 1, in which said body-engageable means includes a circumferentially continuous hollow annular ring which is air-permeable at one axial side, said side being contoured for adaptation to the corneal-scleral region of an eye, and an external connection port to the hollow of said ring for external air-evacuating connection of the same.

12. As an article of manufacture in aid of corneal surgery, a circumferentially continuous hollow annular ring which is air-permeable at one axial side, said side being contoured for adaptation to the corneal-scleral region of an eye, and an external connection port to the hollow of said ring for external air-evacuating connection of the same.

13. Sculpture apparatus according to claim 1, in which said scan-deflection means is radially operative with respect to the direction of beam travel to said one eye, said scan-deflection means including further means for rotating the direction in which the radial deflection is operative.

14. The method of using the apparatus of claim 13, in which said further means is activated in periodic steps of predetermined angular indexing while deactivating said output beam, and in which said output beam is activated during periods of radial-scan action, said periods being between successive angular indexing operations, and beam exposure being limited to assure ablative photodecomposition to the extent of only partial penetration of the cornea, whereby to perform a radial keratotomy on the cornea.

15. The method of using the apparatus of claim 13, in which said further means is continuously operative in the course of a given radial-scan operation, whereby to develop a spirally sequenced course of beam incidence on the cornea, and beam exposure being limited to assure ablative photodecomposition to the extent of only partial penetration of the cornea.

16. Apparatus according to claim 1, in which said scan-deflection means includes means for selectively varying the scanned area of the field.

17. The method of using the apparatus of claim 16, which comprises scanning successive concentric fields of successively varied area in the course of operation upon a single cornea, whereby cornea curvature is re-characterized.

18. The method of using the apparatus of claim 1, in which said scan-deflection means includes means limiting the field of scan action at the cornea to a predetermined fraction of and configuration within the external area of the cornea, and limiting beam exposure to assure ablative photodecomposition only within said configuration.

19. The method of claim 18, in which beam-exposure flux within said configuration is substantially uniform and is to a penetration depth which is but a fraction of corneal thickness, whereby a recess may be carved for acceptance of a corneal transplant conforming to said configuration.

20. The method of claim 18, in which total beam-exposure flux within said configuration is to a greater extent at the optical center of the cornea and decreases smoothly in the radial direction of the perimeter of said configuration, whereby a myopia-correcting new curvature is imparted to the cornea within said configuration.

21. The method of claim 18, in which total beam-exposure flux within said configuration is to a minimum extent at the optical center of the cornea and increases smoothly in the radial direction of the perimeter of said configuration, whereby a hyperopia-correcting new curvature is imparted to the cornea within said configuration.

22. The method of claim 20, in which said means limiting the field of scan action has provision for sequencing a succession of stepped concentric annular increments of said field, and in which beam-exposure flux within said increments is essentially only to the extent needed to complete the fraction of the myopia-correcting new curvature as the same may be required within the applicable increment, whereby a Fresnel-characterized myopia-correcting change is effected in the cornea.

23. The method of claim 21, in which said means limiting the field of scan action has provision for sequencing a succession of stepped concentric annular increments of said field, and in which beam-exposure flux within said increments is essentially only to the extent needed to complete the fraction of the hyperopia-correcting new curvature as the same may be required within the applicable increment, whereby a Fresnel-characterized hyperopia-correcting change is effected in the cornea.

24. The method of using a scan-deflectable pulsed ultraviolet laser beam to selectively ablate the external surface of a cornea, which comprises focusing the laser beam to an elemental spot size which is but a small fraction of the area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma region of

the cornea, and scanning said area in a pattern to impact the cornea with greatest density of pulses per unit area at the optical center and with pulse density decreasing smoothly with increasing radius to the perimeter of said area, whereby a myopia-correcting new curvature is imparted to the cornea within said area.

25. The method of using a scan-deflectable pulsed ultraviolet laser beam to selectively ablate the external surface of a cornea, which comprises focusing the laser beam to an elemental spot size which is but a small fraction of the area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma region of the cornea, and scanning said area in a pattern to impact the cornea with least density of pulses per unit area at the optical center and with pulse density increasing smoothly with increasing radius to the perimeter of said area, whereby a hyperopia-correcting new curvature is imparted to the cornea within said area.

FIG. 1.

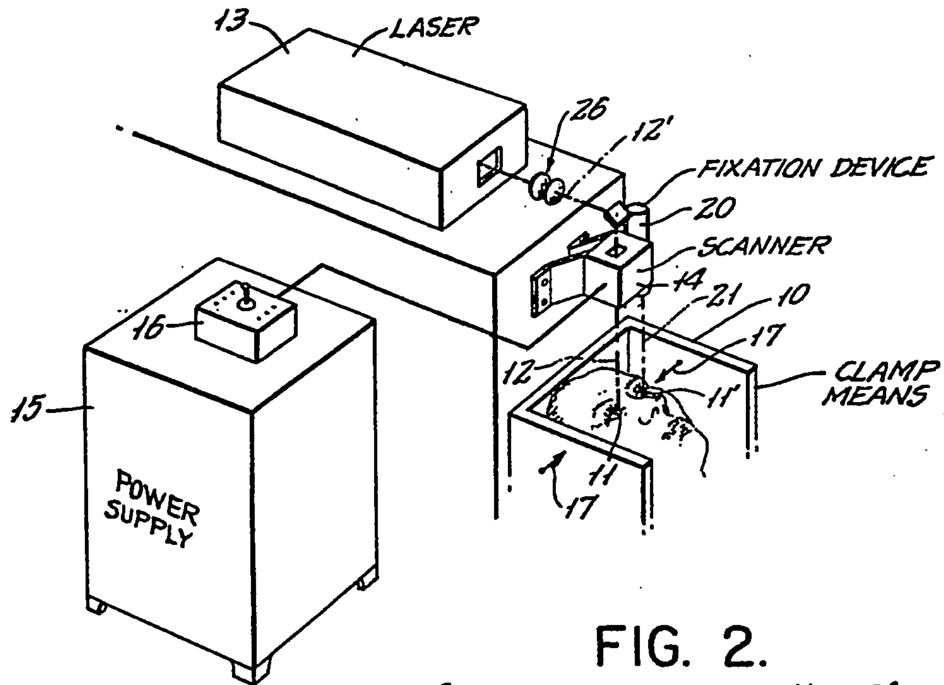

FIG. 2.

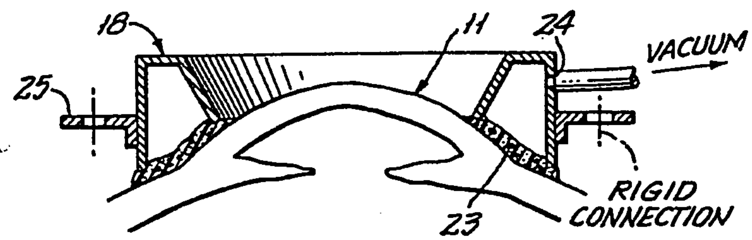

FIG. 3.

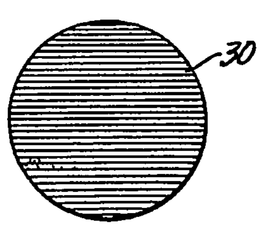

FIG. 4.

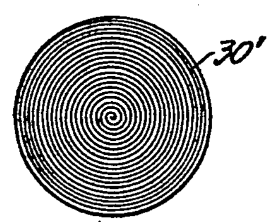

FIG. 5.

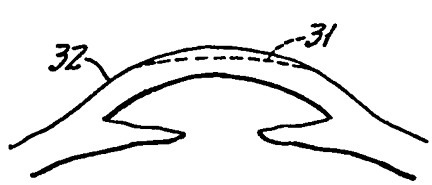

FIG. 6.

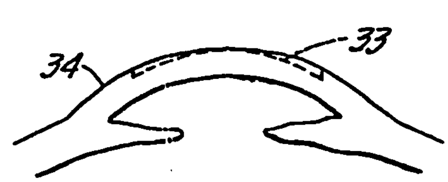

FIG. 7.

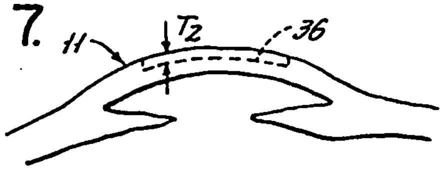

FIG. 9.

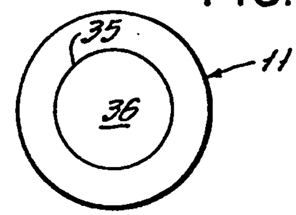

FIG. 8.

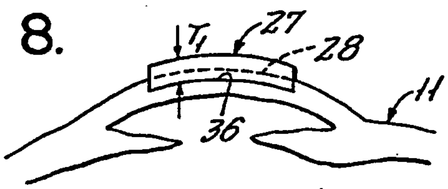

FIG. 11.

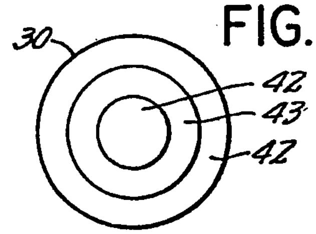

FIG. 10.

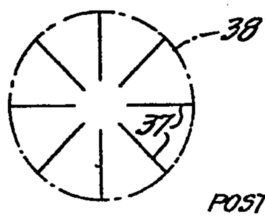

FIG. 12.

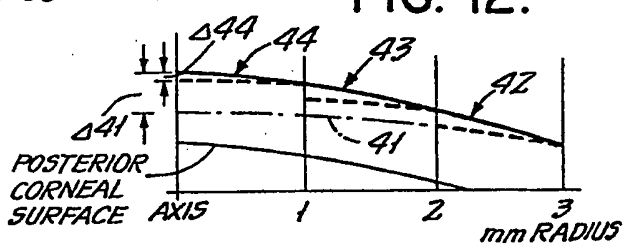

FIG. 13

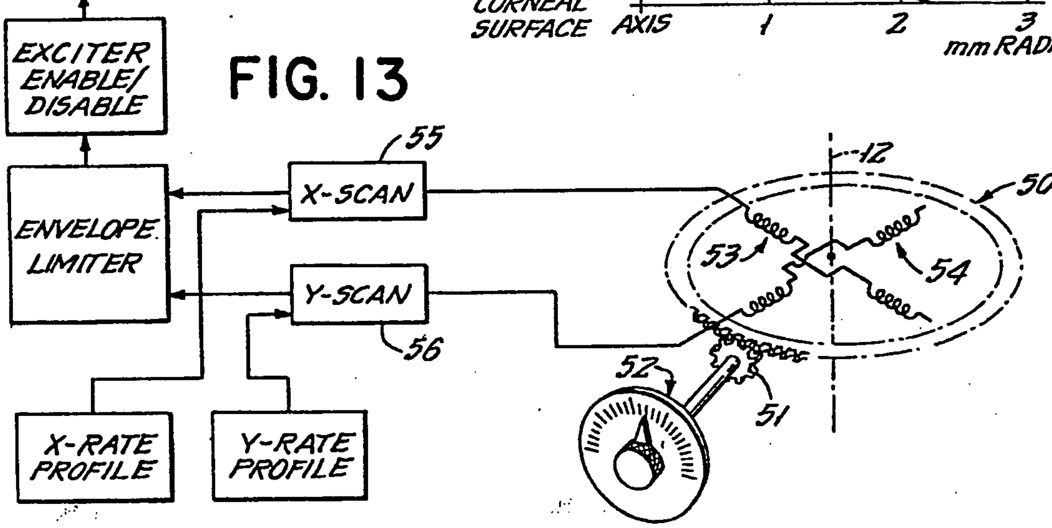

FIG. 14.